British Geological Survey

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Geomagnetism

Review

2018

Geomagnetism

Review 2018

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Key words

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Front and back cover image

The magnetic instrument houses of Lerwick observatory at twilight on Shetland.

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Contents

Introduction

Chris Turbitt demonstrating geomagnetic instrumentation to delegates at the ISCWSA meeting in Inverness in April 2018

The Geomagnetism Team

The Geomagnetism Team of BGS measures, records, models and interprets variations in the Earth's magnetic field. Our data and research help to develop scientific understanding of the solid Earth and of its atmospheric and space environments and help to extend our knowledge of geomagnetic hazards and their impacts. We also provide a range of geomagnetic data, products and services to industry and academia and we use our insights and knowledge to inform and educate.

The British Geological Survey (BGS) is the UK's leading Earth science research institute. BGS is a research centre of the Natural Environment Research Council (NERC), with parent body United Kingdom Research and Innovation (UKRI). Geomagnetism research currently sits within BGS as a science team in the Earth Hazards and Observatories (EHO) science directorate. EHO is part of the Geohazards programme that reports to the Director of Science and Technology and the BGS Executive.

The Geomagnetism Team is primarily based in Edinburgh. In 2018, the Team numbered twenty-five staff either fully or partly engaged in Geomagnetism work. The Team receives support from a range of BGS corporate resources, including Business Administration and Systems and Network Support, as well as from the BGS and NERC Estates teams.

Our remit includes continuous geomagnetic monitoring across the UK. We therefore operate three geomagnetic observatories in the UK, located in Lerwick (Shetland), Eskdalemuir (Scottish Borders) and Hartland (North Devon). Two of our team members are site managers, stationed at the Eskdalemuir and Hartland observatories. We also operate magnetic observatories overseas on Ascension, on Sable Island (Canada), at Port Stanley (Falkland Islands) and at King Edward Point (South Georgia). We oversee and maintain magnetic observatory operations at Prudhoe Bay, Alaska (USA) and Fort McMurray, Alberta (Canada), in association with an industry partner.

Our observatory work and the data we collect is one part of our core function:

Long-term geomagnetic monitoring and allied research to improve our understanding of the Earth and of its

geomagnetic processes, environments and hazards.

In support of this core function, we aim to be recognised internationally as a world leader in

- measuring, recording, modelling and interpreting the Earth's natural magnetic field and its various sources
- modelling and understanding geomagnetic hazard, a component of the space weather hazard to technology and society
- delivering tailored geomagnetic data, products and services to academics, business and the public
- providing knowledge and information for all sectors of society on Geomagnetism science: what it tells us about the Earth and how it can be used in practical ways

People and places in 2018

Introduction

Lerwick variometer enclosure in the snow, April 2018

Objectives and achievements in 2018

The Geomagnetism Team's goals for 2018 included

- operating INTERMAGNET-standard magnetic observatories
- continuing the UK magnetic survey and producing a 2018 UK magnetic model
- providing finalised data and indices to academics and others
- operating the World Data Centre for Geomagnetism (Edinburgh)
- continuing magnetic data partnerships with Met Office, NOAA/SWPC, ESA and others
- producing a 2018 update of the BGS Global Magnetic Model
- completing the space weather collaboration with University of Otago
- continuing the NERC SWIGS space weather project
- carrying on the STFC-funded schools magnetometer project
- continuing the EU-funded EPOS implementation phase project
- advancing our geomagnetic research and publishing results
- providing data products and services to a range of businesses around the world

Some key performance indicators for our outputs in 2018 are as follows:

- >2.9M web page views on our servers
- >10 100 followers @BGSauroraAlert received updates when there was an increased chance of seeing the northern lights in the UK
- >5500 followers received daily space weather updates on twitter @BGSspaceWeather
- 265 global oil industry wells supplied with IIFR data
- 186 global oil industry wells supplied with IFR data
- 108 magnetic bulletins published
- 100% (>98%) UK (overseas) observatory data coverage
- 79 Ordnance Survey map compass references
- 21 off-site presentations/posters
- 21 A-to-Z map compass references

- 21 Customer reports (UK survey & OS; JCO, FMC & SBL observatory service reports; oil industry services)
- 15 field set-ups for IFR services
- 12 journal and conference proceedings papers
- 11 academic and other meetings
- 10 UK repeat station visits and measurements
- 6 positions on scientific and technical geomagnetism bodies (IAGA Executive Committee, IUGG Geohazards Risk Commission, INTERMAGNET Executive Council and Operations Committee x2, IAGA Division V-DAT)
- 6 articles on space weather for RIN ‘Navigation News’
- 5 public lectures, presentations and demonstrations, including Tweeddale Society, ‘Astronomy on Tap’, Midlothian Science Festival, Dalkeith Science Gala, Edinburgh Science Festival
- 4 geomagnetic models (the UK Ordnance Survey reference model, BGGM2018, MEME, WMM2015v2)
- 1 observatory tour
- 3 PhDs co-supervised (Edinburgh x2, Leeds)
- 1 post-doctoral research assistant
- 1 MPhil co-supervised student (Edinburgh)

Tony Swan and Tim Taylor installing a SWIGS system near Whiteadder Reservior in East Lothian

Introduction

Jim Carrington Observatory (JCO) during a service visit in 2018

Looking ahead to 2019

In 2019, we will focus on the space weather and geomagnetic hazard to technology and infrastructure, mainly through the NERC-funded 'SWIGS' project and commercially sponsored studies. We will also focus on developing our global and UK geomagnetic models, taking advantage of our involvement in the extended ESA Swarm magnetic survey mission and, in particular, introducing a new 'high definition' global model for stakeholders.

Major activities to support these activities will include the maintenance and operation of the UK magnetic survey program and of the operation of the BGS magnetic observatories to INTERMAGNET programme standards. We will also continue to produce high quality academic research, leading to better geomagnetic models, data products and publications for stakeholders, such as the public, government and industry.

Key objectives

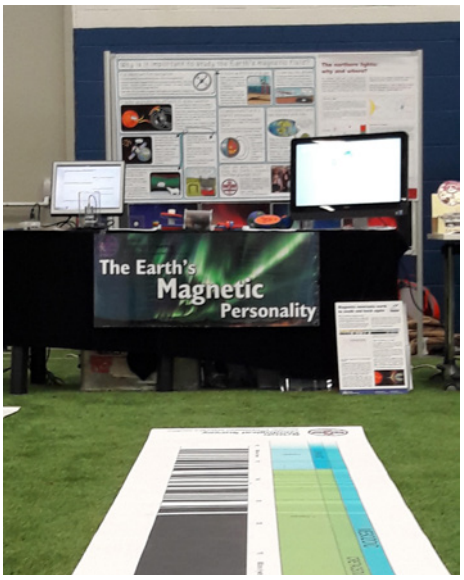
- Geomagnetic monitoring, modelling and hazard assessment of the shallow and deep Earth and of the Earth's atmosphere and space environments
- Applying our data, models and expertise in services and research for academia, industry and society

Main deliverables (in no specific order)

- An INTERMAGNET-standard UK and Overseas magnetic observatory network, obtained through regular observatory service visits and high standards in instrumentation and quality assurance procedures
- Supply of observatory data products to INTERMAGNET, according to the timetable set by the INTERMAGNET consortium
- An annual re-survey of sites in the UK magnetic repeat station network, leading to production of the 2019 national magnetic model and delivery of a report to Ordnance Survey
- Publication of our observatory data and data products online and in the BGS Monthly Bulletins series
- Supply of magnetic index products to the International Service for Geomagnetic Indices (ISGI), according to the timetable set by ISGI
- Operation of the World Data Centre for Geomagnetism (Edinburgh), including an annual 'call for data' and associated quality control activities
- Active participation (through presentations and organisation of sessions) at a number of major international scientific conferences,

including the annual European Geophysical Union conference and European Space Weather Week
- Publication of a number of papers in scientific and professional journals, and the writing of articles for scientific and other publications
- Publication of a Geomagnetism team annual report and hosting of the annual Geomagnetism Advisory Group of Team stakeholders
- Provision of information and other data through the Geomagnetism web site, the main BGS site and by other electronic means
- The supply of solar and geomagnetic activity index forecasts and now-casts to the European Space Agency for the Space Weather Network (SWENET) and the Geomagnetic Expert Service Centre (G-ESC); real-time one-minute data from Hartland observatory to the US Geological Survey and the US NOAA Space Weather Prediction Centre (NOAA/SWPC)
- Support for the UK Met Office Space Weather Operations Centre (MOSWOC) and, as part of the Natural Hazards Partnership project, provision of local and planetary magnetic indices, daily geomagnetic activity forecasts and magnetic data products
- Monitoring and analysis of geo-electric (telluric) measurements at the UK magnetic observatories, partly through a University of Edinburgh MSc project
- Development of the 'Monitoring and Analysis of GIC' (MAGIC) web tool, in association with National Grid for space weather hazard assessment and monitoring
- Production of the 2019 update of the BGS Global Geomagnetic Model

Looking across Port Stanley observatory



Edinburgh Science Festival at the Heriot-Watt 'Oriam' sports facility

(BGGM), using satellite and other geomagnetic data, including data from all BGS operated observatories
- Data collection, QC and model development leading up to revision of the World Magnetic Model 2020 and the 13th generation International Geomagnetic Reference Field
- Delivery of geomagnetic observatory data and magnetic field products, including daily geomagnetic activity forecasts, to support geophysical survey companies and directional drilling operations, through the 'In-Field Referencing' (IFR) and 'Interpolation IFR' (IIFR) services
- Provision of observatory facilities for calibration and testing of instruments
- Year 2–3 of the NERC 'Highlight Topic' grant studying 'Space Weather Impacts on Ground-based Systems' (SWIGS), in association with nine UK universities and Research Centres and an external stakeholder and partner group of academics and industry representatives
- Implementation of web services to, and metadata standards describing, geomagnetic data and models, as part of the European Plate Observation System (EPOS) project, funded by the EU under the Horizon 2020 programme
- Provision of data products for the ESA Swarm 'Data, Innovation and Science Cluster (DISC)', set up by ESA in support of the goals of the Swarm satellite magnetometry mission

Technical, observatory and field operations

Rainbow over Loch Broom at the repeat station site at Leckmelm which was revisited in 2018

UK and overseas observatories

BGS operates three geomagnetic observatories in the UK and six observatories overseas to supply high quality, real-time measurements that underpin products for both commercial and academic users. We also take a leading role in expanding the global observatory network, with the aim of improving global magnetic field modelling and for local commercial applications. The UK observatories achieved a 100% unbroken data supply in 2018.

Technical developments

In October 2018, we started the migration of all observatory data loggers from the QNX real-time operating system to Linux. This became necessary because of reliability issues with the QNX6 platform running on 64-bit PCs. The migration to Linux will present challenges in producing a true 'real-time' operating system, as a number of the sensors used in BGS observatories require the operating system to time-stamp data. Work has however progressed well, with two software sprints in October and December, and we foresee that a Linux system, recording data from the Lemi-025 fluxgate magnetometer, will be ready early in 2019.

The Lemi-025 magnetometer, which is capable of returning 1-second data, has now been installed at all three UK observatories. Installation modifications have seen an improvement in its long-term stability. However, there still remain questions as to whether long-term standards, required by INTERMAGNET, are being met by the instrument. Testing will therefore continue throughout 2019 to determine the instrument's performance. Fast sampling 1-second scalar magnetometers have been installed alongside the Lemi magnetometers at all three UK observatories. These will help reduce any aliasing effects caused by timing errors between the scalar and variometer sensors and will deliver a 'true' 1-second recording system.

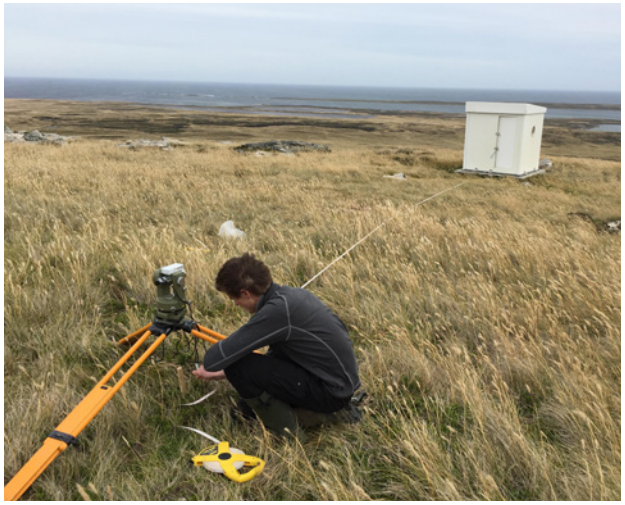
A GPS controlled display clock was also developed for use when making absolute observations at magnetic observatories. This will replace the existing hand-held GPS and stop watches currently used at the overseas observatories.

Magnetic observatories

Service and calibration visits were made to all three UK observatories as well as to many of the overseas observatories: Sable

Island and Fort McMurray in Canada; Jim Carrigan Observatory in Northern Alaska; and Port Stanley in the South Atlantic Falkland Islands. Travel to the observatory on Ascension remains difficult, due to an unserviceable main runway on the island. A service visit is planned for King Edward Point, South Georgia in the Austral summer of 2019.

On Sapper Hill to the west of Port Stanley, the variometer continues to suffer radio-frequency interference (RFI) from transmitters located on the hill. A similar problem at the absolute hut saw its relocation in 2013, after a site survey using a theodolite-mounted fluxgate identified an area free from RFI. A service visit in February 2018 used the same technique to identify a possible new location for the variometer enclosure. However, no similarly 'clean' area could be found. The installation of new filters, along with shortening of the cables within the fluxgate enclosure improved signal-to-noise at the site for a number of months. However, the switching on of a newly installed 4G antenna in August saw a dramatic increase in noise levels. The long term viability of the observatory therefore looks increasingly untenable and a potential new observatory location has been located some 3 km to the east of the current site. Long-term testing of this new site using a temporary magnetometer installation will begin in early 2019.



Surveying for RFI at Port Stanley Observatory, Falkland Islands

At Eskdalemuir observatory in September, an upgrade to the local area electrical supply presented challenges in maintaining continuous data supply. Thanks to the efforts of a number of staff, this was achieved throughout a two-week period during which time the entire site was supplied by standby generators and which saw the presence of a number of contractors' vehicles on site. Further infrastructure upgrades were carried out at both Eskdalemuir and Hartland during 2018.

The Global Network and the 2018 IAGA Observatories Workshop

An overview and performance evaluation of the SWIGS field monitoring system was presented at the biennial IAGA Workshop, hosted by the Conrad Observatory, Austria. BGS was represented on a panel discussion on EPOS metadata and BGS also helped lead a week-long summer school course in observatory techniques, prior to the main workshop.

BGS continues to be active on INTERMAGNET committees and plays a leading role in assisting international observatories. Through the INDIGO project, BGS assisted magnetic observatories in Costa Rica, Argentina, Mozambique and Indonesia in 2018.

UK Repeat Station Network

The 2018 magnetic repeat station programme re-visited ten measurement sites in the east of Scotland and England, the central Highlands of Scotland and south west England. Of particular note was the observation of an easterly magnetic variation on the 27th September at Dunwich Heath in Suffolk. This is the first easterly variation seen in the UK since observations began in the London area some 370 years ago.

BGS also carried out a number of magnetic survey measurements around Loch Ness. This helped to constrain a regional model used in support of a commercially operated down-hole tool testing facility.

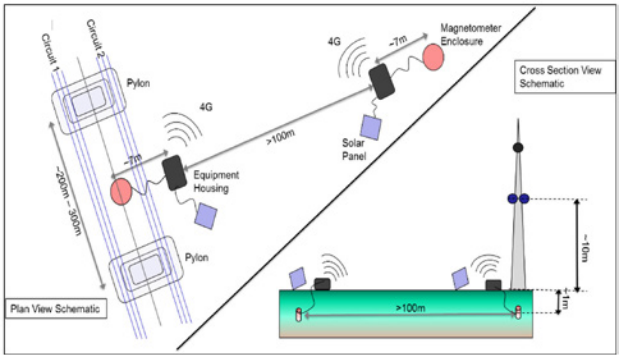
Technical, observatory and field operations

Underline differential magnetometer system in-situ at Whiteadder, Scottish Borders

A remote magnetometer system supporting the SWIGS project

The Geomagnetism Team has designed, manufactured and deployed six self-contained differential magnetometer systems, in support of the 'Space Weather Impact on Ground-based Systems' (SWIGS) project. With these mobile systems, we are able to estimate Geomagnetically Induced Currents (GIC) simultaneously at six sites under high voltage overhead cables in the UK power transmission network.

The impact of GIC, caused by severe space weather, on ground-based infrastructure is a well-known phenomenon that, in extreme cases, has led to significant disruption to power supplies and technologies in countries around the world. However, the lack of readily available GIC data from network operators presently limits the verification of BGS models of GIC flow in the UK power grid. The SWIGS project specifies simultaneous monitoring of GIC at six sites in the UK. These sites provide proxy measurements of the induced currents in nearby high-voltage overhead lines. The Geomagnetism Team has therefore developed a remote magnetometer system capable of delivering this data in near real-time, using a differential magnetic variometer method.



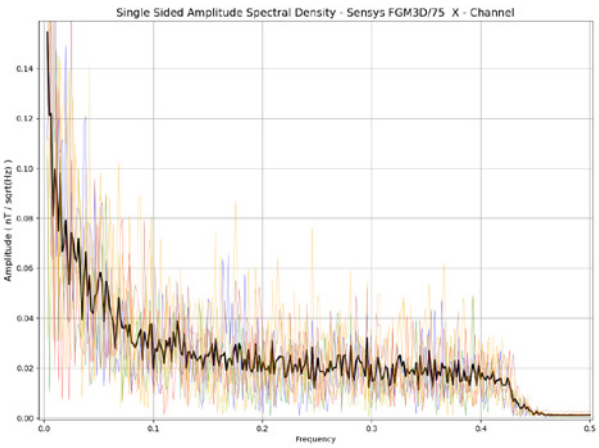
Schematic of SWIGS magnetometer system

The bandwidth of interest is between 10 and 10 000 seconds and the signal resolution needs to be of the order of 1nT. The design for each system comprises a Sensys FGN3D magnetometer coupled with an Earth Data EDR209 3-channel digitiser. The performance of the Sensys FGM3D variometer was tested and calibrated at the BGS mu-metal shield testing facility at Eskdalemuir Observatory, to ensure it met the sensitivity requirements of the project.

An impulse response was simulated using an on/off step current with a period of 1800 seconds. A maximum attenuation of -0.1dB was determined within the frequency band of interest. The noise floor was obtained

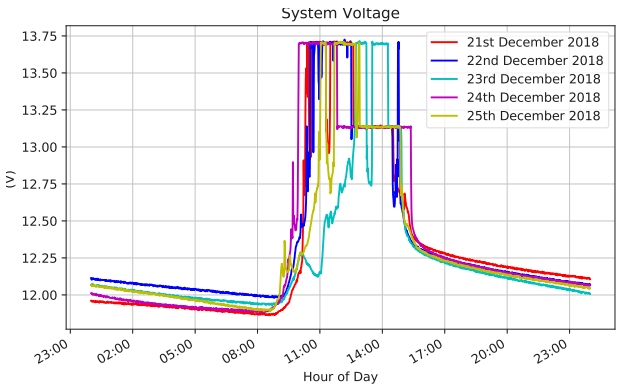
from ten periods of 600 seconds operation within the shield. The system was found to have a noise floor of <0.02nT/√Hz within the frequency range 0.1 to 0.5Hz. Although falling short of the specification for instruments at the BGS permanent observatories, these results are well within the sensitivity requirements of the SWIGS project.

Unlike the long-running BGS observatories, these remote observatories are off-grid and thus must be self-sufficient in electrical power for up to six months. To meet this requirement each system is powered by two 90Ah batteries, recharged by a 270W solar panel via a charge regulator. This system has proved sufficient even during the Scottish winter, with batteries returning to full charge within 45 minutes of sunrise.



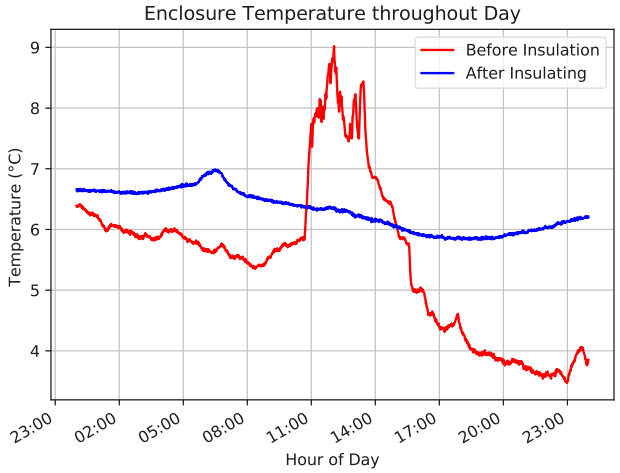
SWIGS remote magnetometer system noise floor—the black line is the average of ten 600 second cycles

Temperature stability was initially expected to be achieved by burying the magnetometer to a depth of around one metre. In testing, however, we noted that burying the variometer alone was insufficient to provide the temperature stability required. Solar heating of the soil resulted in temperature variations of >4°C over any three hour time window. The enclosure was therefore modified to include thermally insulating material, which reduced the temperature variations to <1°C over the same period.



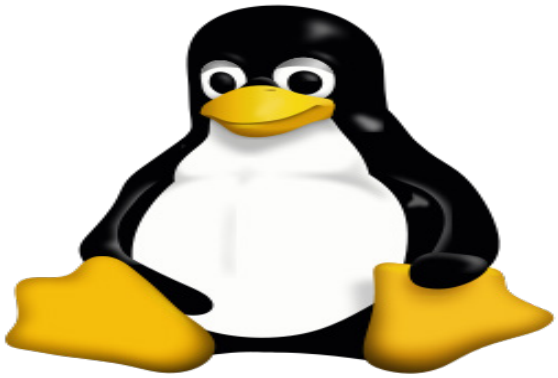
The solar panel charged system batteries returns to full charge shortly after sunrise, even throughout a Scottish winter. Shown are battery voltages during the day for the period of the winter equinox to Christmas Day

Three magnetic components are recorded every second and the temperature and battery voltage are sampled once per minute. Near real-time data are returned via 4G routers with data packets transmitted via the well established and robust Seedlink protocol. A data collection system, written in Python, handles data collection and initial QC. The systems have proved to be resilient to in-field conditions, surviving both storms and inquisitive livestock.



Thermally insulating the enclosure has reduced the temperature variation caused by solar heating of the enclosure roof

Technical, observatory and field operations



Tux, the mascot of the Linux operating system. Attribution: Larry Ewing and The GIMP

Information technology systems in the Geomagnetism Team

Information Technology (IT) is fundamental to the work of the Geomagnetism Team, from the recording of data at the observatories, to data transmission to Edinburgh, through to creating models on High Performance Computers and the building of software that provides easy access to our data. Everything that we do in the Geomagnetism Team relies on computer systems and software, much of which we need to create ourselves. This section presents the highlights of the year's work from the team of engineers and scientists responsible for delivering IT in geomagnetism.

Solaris to Linux migration

This project, to move our software from the Solaris operating system to the Linux operating system, has been ongoing since 2011. During 2018:

- We had 27 progress meetings, continuing the work to convert and test all real-time production software. In parallel, we completed work to convert heritage FORTRAN software to double the numerical precision thus improving computational accuracy
- The on-site backup real-time processing system transitioned to Linux on 2nd August. The off-site backup real-time processing transitioned on 25th October and the primary data processing system moved over to Linux on 26th November

This completed the move to Linux for our most complex business-critical systems. Work will continue through 2019 on our non-real-time software, with the aim of removing the Solaris service completely by mid- 2020.

Data collection

Collection of geomagnetic and electric field data at observatories is managed by software written by BGS that runs on the QNX real-time operating system. However,

changes to QNX now make it unsuitable for our future needs. We are unable to run QNX on 64-bit computers and are also unable to buy suitable 32-bit computers. Recognising this last year, we conducted a review of suitable technology and decided to migrate the software to Linux. Two 'sprint' weeks took place in 2018 (November and December) to work on this migration.

Because of the importance of electric field (telluric) data to the Team's research, we upgraded the software used to transfer these data from the measurement sites to the Edinburgh office. These upgrades are designed to make the software more reliable and easier to use, as well as creating data formats better suited to long term preservation.

Magnetic modelling

- A one week-long 'sprint' was undertaken in January 2018, to improve the satellite data selection code used in production of the BGGM
- The BGGM source code was updated to use a new coefficient file format that supports higher resolution models
- An out-of-cycle World Magnetic Model (WMM) was released, owing to unexpected magnetic field changes in the northern polar region and the consequent degradation in WMM accuracy. The WMM web service was also updated to allow access to both the WMM2015 and the out-of-cycle WMM release

Web services

- A number of web services for the European Plate Observing System (EPOS), covering both BGS and other data sets, were connected to the EPOS web portal
- The BGGM web service is now being used by customers. Other web services, such as the WMM and IGRF, are also seeing good use
- Parts of the Geomagnetism community metadata database, prepared under the EPOS project, were made available to INTERMAGNET in the form of a web service

High-performance computing

- A one day HPC global field modelling training course was hosted by BGS and Edinburgh Parallel Computing Centre (EPCC) at the Lyell Centre, as part of an eCSE code development grant, in December 2018
- The BGS MEME (Model of Earth's Magnetic Environment) code was delivered by EPCC and tested on the BGS HPC cluster

IFR services

- An IFR 'multi-cube' (multiple data hypercubes covering a large geographical area) capability was made available on our online IFR service
- Several subscriptions for the online IFR calculator were taken up

Best practice

- Continuous Integration was introduced on a number of Geomagnetism software projects. This automates some parts of the development process, improving productivity and reducing mistakes
- All current software development projects now use Git and GitLab for software version control

Technical, observatory and field operations

INTERMAGNET meeting in Vienna, July 2018. Photo copyright ZAMG

Geomagnetism Team contributions to the World Data Centre and INTERMAGNET

The Geomagnetism Team operates a World Data Centre (WDC) for Geomagnetism under the umbrella of the International Science Council's (ICSU) World Data System. Geomagnetism staff also have leading roles in the INTERMAGNET global network of observatories. We describe updates and events of interest relating to the WDC and INTERMAGNET over the past year.

In order to make increasingly sophisticated models of the Earth's magnetic field, we need access to the widest possible coverage of high quality geomagnetic data. In recent times, this has led to use of an increasing quantity of satellite survey data from the ESA Swarm mission. However, land-based observations continue to be important, both in their direct importance to geomagnetic modelling and in their support for and calibration of satellite measurements.

Our interest in operating a World Data Centre (WDC) for Geomagnetism is to simplify access to the largest possible volume of observatory data, through actively soliciting data contributions from external institutes and making it available in one place and in one data format. On behalf of the WDC, the Geomagnetism Team has also continued to work towards Core Trust Seal certification and has taken advantage of EPOS activities on observatory metadata to begin to improve the WDC metadata records.

Geomagnetism staff members chair the INTERMAGNET executive council, the INTERMAGNET operations committee and the INTERMAGNET Magnetic Observatory applications sub-committee. Our strong presence in INTERMAGNET therefore allows us to play a leading role in the development of the standards and systems used for ground-based geomagnetic observatories, to the benefit of the international field modelling community, within which BGS also takes a leading role.

During 2018, INTERMAGNET completed its 24th annual publication of definitive data, consisting of continuous recording of the magnetic field during the year 2014, at a one-minute sampling interval, from 112 observatories across 37 countries. For the first time, data publication was by USB stick (instead of DVD). BGS staff were involved in creating this publication, including checking the quality of data submitted for inclusion. We also worked on the publication for the following year

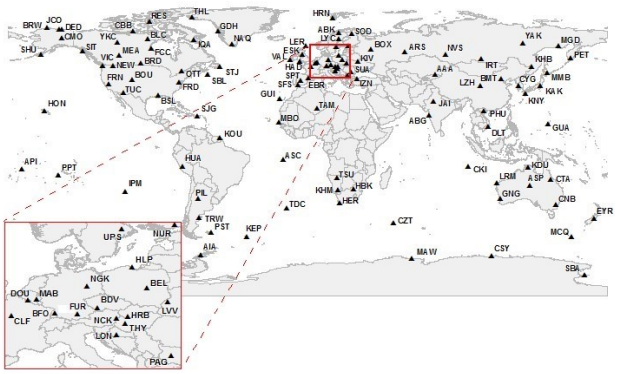
(2015), which will be INTERMAGNET's 25th year of publishing data. To celebrate, INTERMAGNET will produce a USB stick containing all 1-minute definitive data submitted to INTERMAGNET between 1991 and 2015.

2015 will be the final year for which INTERMAGNET publishes data on a physical medium (CD, DVD or USB stick). From 2016 onwards, INTERMAGNET data will be published under a Digital Object Identifier (DOI) and the 'landing page' for the DOI (a web page specific to the publication of a body of data) will be used to hold and distribute the data to users. BGS staff have been heavily involved in the work to prepare for this, consulting with the institutes that provide the data to reach agreement on a modern, 'machine readable' license under which the data can be published. We have also been working with partners at GeoForschungsZenturm (GFZ), Germany, to agree ways in which the necessary metadata can be formatted to the international standards required for a DOI. We have created a draft DOI for INTERMAGNET's 2013 data and submitted it to two rounds of comment and revision by the community. Once this first DOI is completed, we will use this as a 'template' for the production of other DOIs for INTERMAGNET's annual definitive data publications.

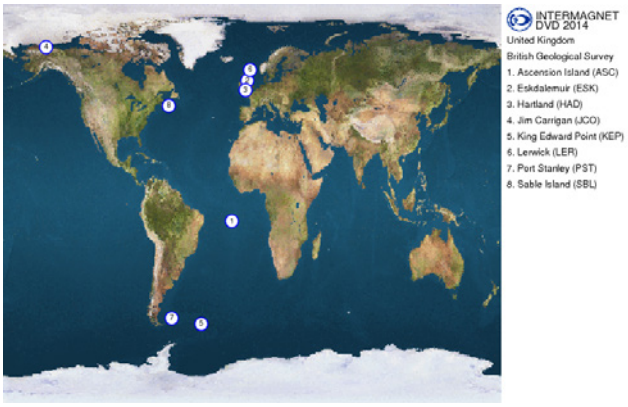
Quasi-definitive data (QDD) is the name of a data product that INTERMAGNET has been championing for several years. The idea behind QDD is to provide an opportunity for institutes to produce data that is close to the definitive data standard, but that is published more rapidly than definitive data can be. To have confidence in the QDD, checks must be carried out periodically to verify that the data are sufficiently near to their definitive equivalent. BGS supplied software and expertise to help in the verification of QDD for the 2015 data set. Seventy observatories (more than half the network) submitted quasi-definitive data in 2015. Only six months of data from four observatories were found to be outside the required tolerance (just 0.5% of all data).

BGS staff contribute to software used within INTERMAGNET and in the global scientific community. In 2018, we completed changes to the software distributed with the annual definitive data publication. We also completed a new piece of software for converting between the most widely used geomagnetic data formats. Software that INTERMAGNET provides is available from http://intermagnet.org/publication-software/software-eng.php.

BGS is active in preserving the INTERMAGNET observatory network, both through campaigning for observatories under threat of closure as well as acting as advisors to new and established observatories with the ambition of meeting the standards required to join the network.



INTERMAGNET observatories contributing to the 2014 annual definitive data publication.



BGS observatories contributing to the INTERMAGNET 2014 annual definitive data publication

Technical, observatory and field operations

The European Plate Observing System

The European Plate Observing System (EPOS) is an €80M European project that aims to provide a simple, unified way to access European Geoscience data. BGS has played a leading role in several parts of the project, now in its implementation phase. Staff from the Geomagnetism Team have key roles in ensuring that Geomagnetic data are amongst the products on offer from EPOS.

Many areas of science generate large volumes of data. Making these data easier to access increases the value of the data, to scientists as well as to government, industry and the public. In Geomagnetism, we have already developed good mechanisms for sharing data within our international community. EPOS adds to this capability by providing guidance and standards on how to make any geoscience data available in ways that simplify the combining of data from different geoscience domains. The goal of EPOS is that this 'interoperability' of data across science domains will help new science to arise, for example by providing tools that make it easy to combine data from different areas of expertise.

One of the main areas where EPOS has provided funding and support to the magnetic observatory community is in the design, development and management of a metadata system for global magnetic observatory metadata. Currently our metadata is fragmented: it is held in several locations and is not connected (the World Data Centres for Geomagnetism, the INTERMAGNET web site and unstructured text on INTERMAGNET annual data publications). With the help of EPOS, we have designed a metadata database that will serve the needs of the community, as well as meeting international metadata standards, allowing metadata from our community to be presented alongside metadata from other geoscience domains.

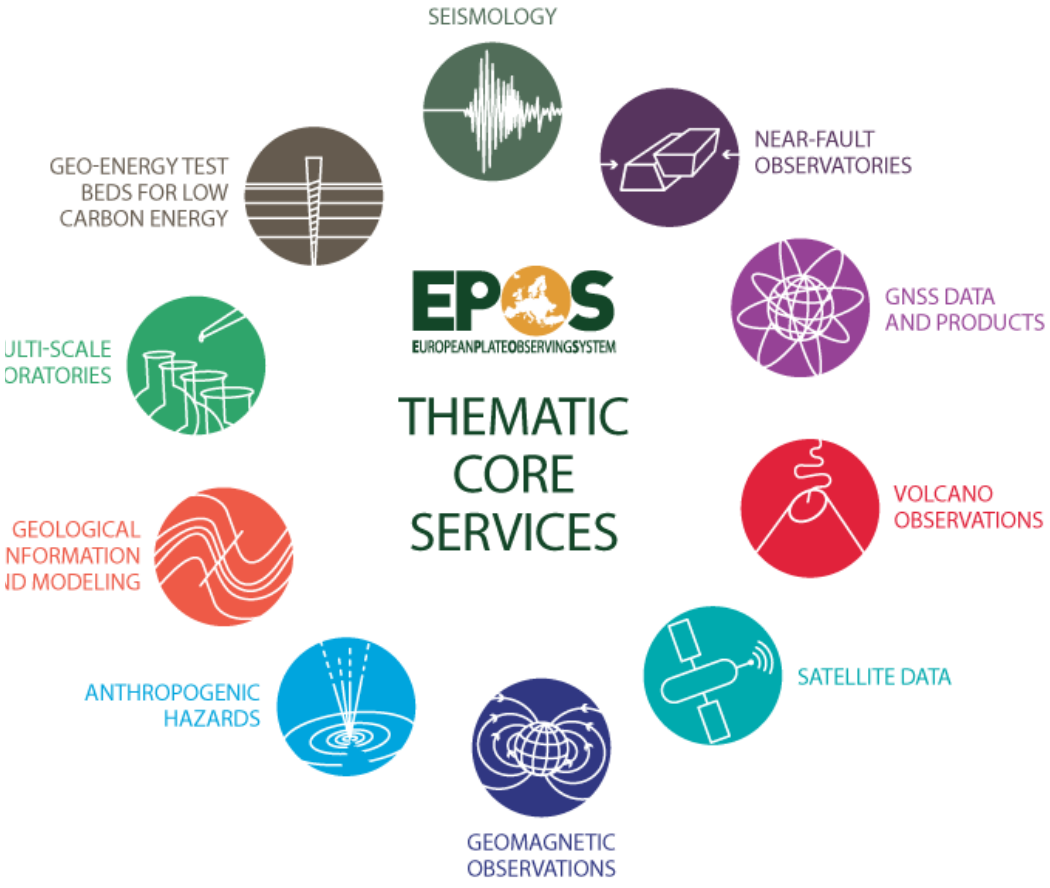
The design of the metadata database has been reviewed by experts in both geomagnetism and in database/metadata design. BGS staff led this work, being ideally placed to do so, through strong leadership roles in the international geomagnetic community (IAGA, INTERMAGNET and the World Data Centre for Geomagnetism (Edinburgh)). Some INTERMAGNET metadata have already been loaded to the database and work is now moving on to importing metadata from the World Data Centre for Geomagnetism (Edinburgh). Further work is required to tackle the more complex task of loading data from unstructured text files published over 25 years by INTERMAGNET.

EPOS has also been influential in other areas within the geomagnetic community, helping us look at how we license our data and providing expertise on the creation

of digital object identifiers (DOIs) for INTERMAGNET publications. Because of this work, INTERMAGNET is now moving from an informal 'home grown' license for its publications, towards the use of Creative Commons licensing. It is also on the verge of publishing its first DOI for a data set. Both these advances are the result of long and detailed consultation with the community, which staff from BGS geomagnetism have led. The creation of a user feedback forum, under EPOS auspices, has been vital in our ability to hold this conversation with our users. BGS geomagnetism staff have also led on other areas within EPOS, such as on methods by which time series data across many different science communities can be made available in a common format for visualisation.

Alongside the work already described, one of the main goals of EPOS is to make geoscience data available via a single portal. Geomagnetism is one of ten science domains in EPOS that are contributing to this work. The geomagnetism contribution to the portal includes provisional and definitive observatory data from INTERMAGNET and the WDC (Edinburgh), variometer data from the IMAGE network, geomagnetic indices and events from the International Service of Geomagnetic Indices (ISGI) and access to models such as the International Geomagnetic Reference Field (IGRF) and the World Magnetic Model (WMM). BGS staff have led the work to create and integrate web services into EPOS that give access to these data and services.

The EPOS implementation phase project will end in September 2019. However, this point then marks the start of the EPOS operational phase, governed by a new legal entity, the EPOS 'European Research Infrastructure Consortium' (ERIC). Individual countries, including the UK, have agreed financial contributions to the ERIC, which was formally established in November 2018. BGS geomagnetism staff will continue to guide and support the work of EPOS as it moves from implementation to operation.



The EPOS Thematic Core Services diagram. CC-BY-SA 4.0

SWIGS
SPACE WEATHER IMPACT ON GROUND-BASED SYSTEMS

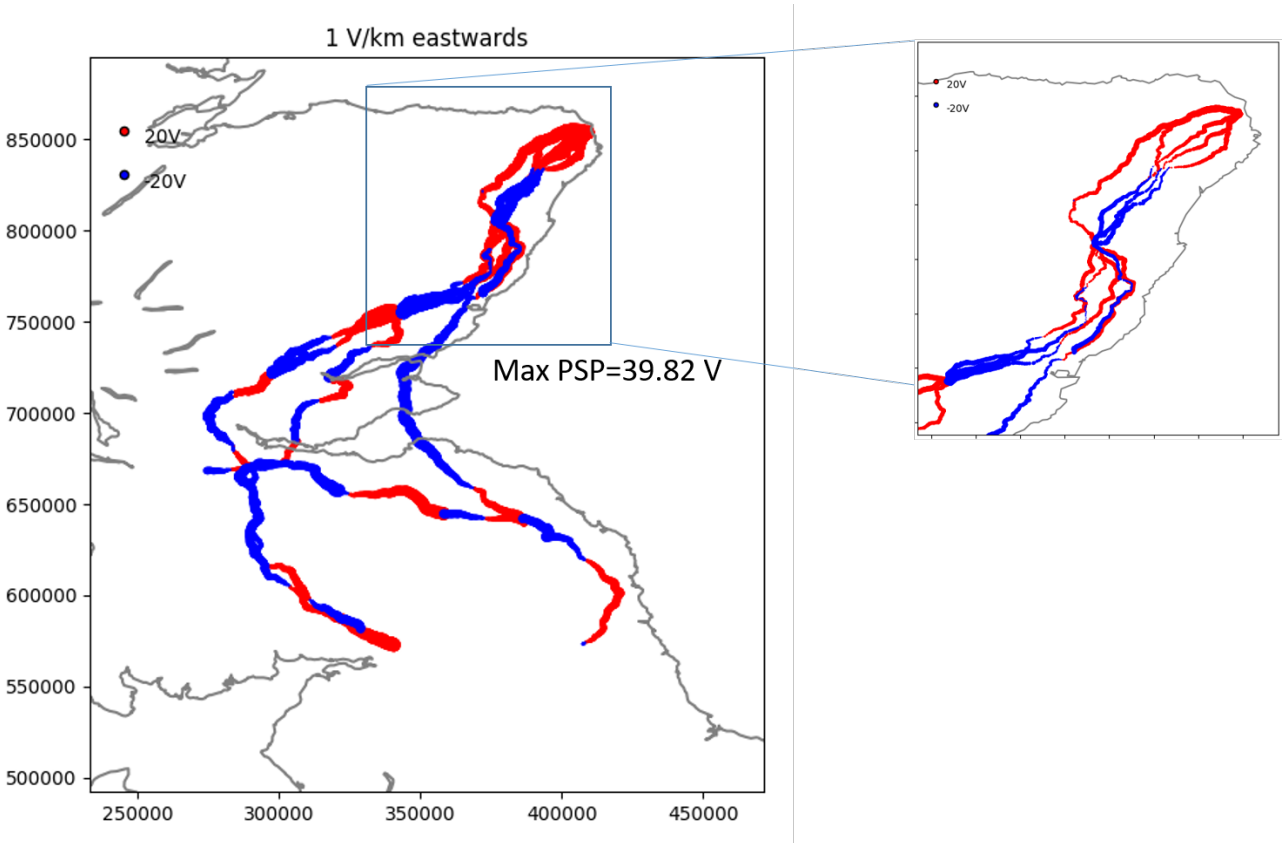
Space weather impacts on ground-based systems

The SWIGS project is a NERC-funded 'Highlight Topic' project to investigate how space weather affects conducting infrastructures on the ground. As the BGS-led project entered its second year in 2018, our work continued on researching and answering the questions in the four major work packages. We report on progress thus far.

The four-year NERC-funded SWIGS project transitioned from year one to year two through 2018. Each of the four work packages continued to produce new research outputs (see the 'Geomagnetism Annual Review 2017' for a description of the project). BGS primarily participates in Work Packages 2 and 4, with the overall project managed by Principal Investigator Alan Thomson.

SWIGS members organised a Specialist Discussion meeting at the Royal Astronomical Society (RAS) in March, participated in the EGU conference in April and the AGU conference in

Alan Thomson presenting at the SWIGS annual project meeting in Lancaster University (September 2018)



Pipe-to-soil potential (Volts) in the Scottish gas pipeline network for a geo-electric field of 1 V/km in an eastward direction

December, and had their annual workshop in Lancaster in September. The RAS meeting attracted 75 participants with twelve talks and six posters. An article based on the presentations and discussion was published in the RAS Astronomy and Geophysics journal in August 2018. The annual SWIGS progress workshop meeting in Lancaster in September lasted two days.

A database of UK rail network track anomalies for days across the October and November 2003 storms was acquired and analysed, led by Mike Hapgood (RAL Space, STFC), with input from BGS staff. A degree of correlation between unexplained events (such as panel 'buzzing', system failures or signalling issues) and high geomagnetic activity was found. In parallel with this research, we also held discussions with engineers from Atkins Rail with regards to the potential effects of space weather on the rail network.

The second season of the magnetotellurics (MT) campaign continued from April to October 2018, with data from eight more MT sites in southern Scotland and northern England being collected by the team at Southampton University. These data are currently being processed to produce a consistent 3D model of the regional conductivity across the northern part of Britain. Once this work is complete, further MT measurements will be made in 2019, with a view to cover any gaps in the conductivity model. Archive MT datasets from Leeds University, collected from MSc theses and analogue campaigns, were reviewed and assessed by Kathy Whaler (University of Edinburgh).

Work Packages 1 and 3, which concentrate on the external drivers of space weather effects on the ground, continued to be productive, for example, with research into extremes of magnetic field change and how the solar wind impacts the magnetosphere.

Photo of SWIGS DMM station close to Ilderton, Alnwick, Northumberland

Differential magnetometer measurements of GIC in the UK power grid

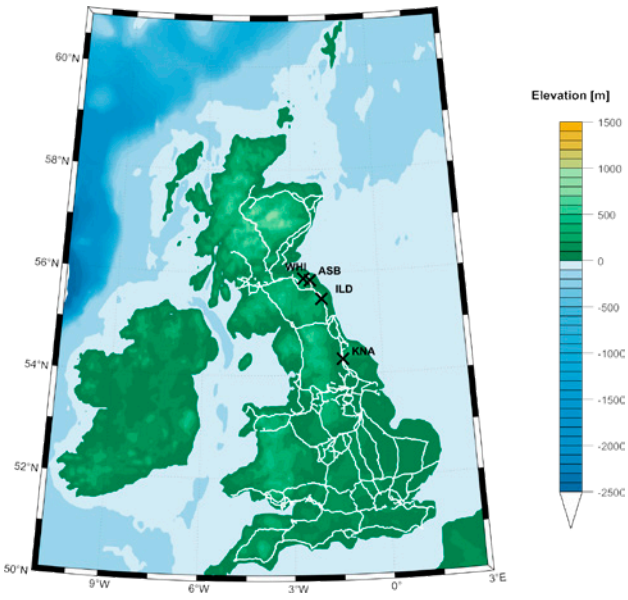
SWIGS (Space Weather Impacts on Ground-based Systems) is a NERC funded three-year project, comprising ten UK based institutes and led by the Geomagnetism Team. One research focus is improving the modelling of Geomagnetically Induced Currents (GIC) in the high voltage power grid by increasing the number of direct observations of GIC using the Differential Magnetometer method (DMM). In 2018, the Geomagnetism (Engineering) Team designed and assembled several DMM instruments to be deployed across the UK. Here we present some results of the first year's field campaign.

The Differential Magnetometer Method

The Differential Magnetometer Method (DMM) to observe GIC in power lines was first developed and implemented by scientists at the Finnish Meteorological Institute. A DMM system consists of two fluxgate magnetometers with data loggers, one magnetometer placed directly under a high voltage power line carrying GIC, and a second placed at a remote site a few hundred metres away, with both powered by solar panels. The difference in the magnetic field recorded between the two instruments allows a calculation of GIC in the power line via the Biot-Savart law of electromagnetism. In BGS systems, measured GIC data are transferred in real-time back to the Edinburgh office over the 4G mobile phone network. We anticipate that each system will remain in place for around six months at each site, before the instruments are moved to a new location, with the intention of sampling GIC at various locations in the UK high voltage grid over the course of three years.

Field work

Four DMM systems were assembled and deployed in 2018 to field sites that were chosen using several criteria. For example, we identified high voltage lines near to substations that suggested high GIC from past modelling of storm scenarios such as the March 1989 and March 2015 severe magnetic storms. Landowners were asked for permission to host our instruments and we were pleased with the high level of interest and cooperation we found. The first DMM site was installed

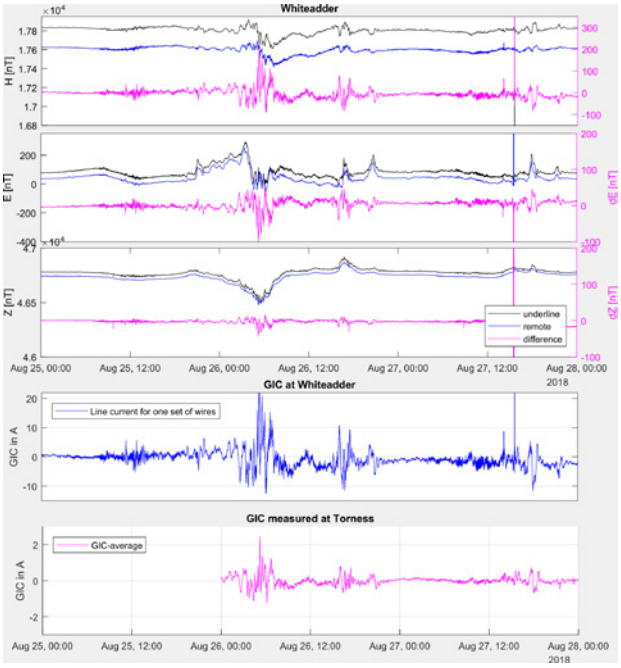


Map of 2018 DMM deployments and the high voltage power grid in the UK (white lines). WHI – Whiteadder, East Lothian; ASB – Abbey St. Bathans, Scottish Borders; ILD- Ilderton, Alnwick; Northumberland, KNA – Knayton; Thirsk, Yorkshire

at Whiteadder in the Lammermuir hills (East Lothian), under the power line from the Torness power station to Edinburgh. Due to the remoteness of this site, two large mobile phone antennas were required to boost the signal. Since August 2018, the Whiteadder site has provided reliable data. More stations in the Scottish Borders, Northumberland and Yorkshire followed later in the year. The instrument in Northumberland suffered damage by cows, which led to some re-design to improve the robustness of the installation. However, eventually the site was vacated earlier than scheduled, due to further bovine damage to the equipment.

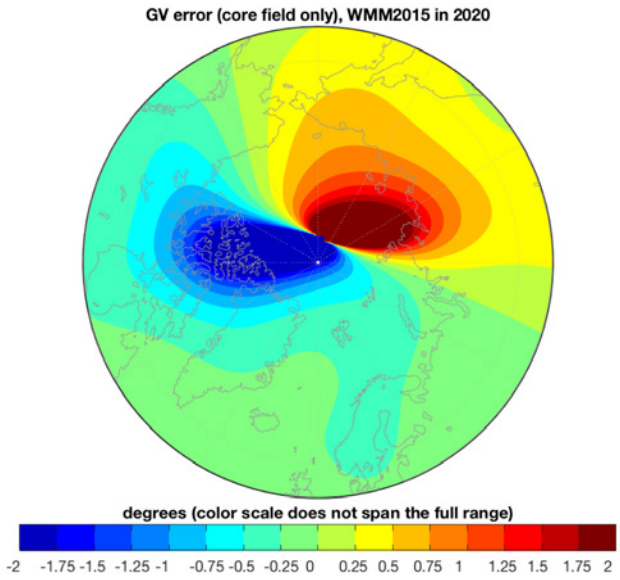
First GIC data

2018 has been relatively magnetically quiet with only a few minor geomagnetic storms. The largest event was a G3 class storm (equivalent to Kp of 7) over 24–26 August. This followed a prolonged period of southward interplanetary magnetic field in the solar wind, as a result of a solar coronal mass ejection. Fortunately, the installation in Whiteadder was already up and running. Differences in the magnetic field between the underline and remote magnetometer of about 200nT were recorded, translating into GIC of about 20 A. Scottish Power later supplied GIC data from a 'Hall probe' on one of the transformers at the Torness substation. The DMM and Hall probe data are reassuringly similar, though there is a difference in amplitude, which we think may be due to GIC in a number of different lines, in addition to the Whiteadder line, entering the transformer and cancelling out. Another G3 event was captured in November 2018 at all four DMM sites and data analysis and GIC modelling is currently underway.



Magnetic field variations at station Whiteadder during the G3 storm of 26 August 2018 and the GIC signal derived from the difference in recordings at underline (black lines) and remote(blue) magnetometer. GIC measurements in the near-by Torness substation were provided by Scottish Power

Global geomagnetic field modelling



Northern hemisphere grid variation (adjusted declination) error predicted by 2020 from the original WMM2015 (WMM2015 Performance Whitepaper, 21-Mar-2018, NOAA-NCEI)

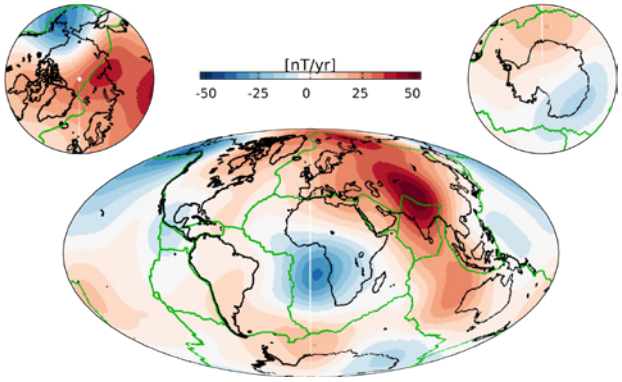
BGS global magnetic field modelling research has impact beyond our geomagnetic referencing services for industry. Our work also supports satellite magnetic survey missions as well as instrument refurbishment and deployment at magnetic observatories in several developing countries. Some of the largest organisations and many millions of smartphone users worldwide also rely (often unknowingly) on outputs from our magnetic models, which support various navigation technologies they use.

Out-of-cycle World Magnetic Model

We contribute to several internationally recognised field-modelling activities, one of which is the World Magnetic Model (WMM). The WMM is a joint product of BGS and the US National Oceanic and Atmospheric Administration (NOAA), funded by the UK Defence Geographic Centre and US National Geospatial-Intelligence Agency. The WMM is the global standard model for navigation, used by organisations such as NATO, the Ministry of Defence, the US Department of Defense and the Federal Aviation Administration. The WMM is embedded in smartphone operating systems such as Android and iOS, enabling a phone to orient itself, for example for use by mapping or augmented reality apps. The WMM is also found in many GPS navigation systems such as in-car navigation systems. The WMM provides a prediction of changes in the magnetic field arising in the Earth's core, together with associated uncertainties, for five years into the future. The WMM was last updated in 2015, to cover the period 2015.0 to 2020.0.

In March 2018, NOAA announced that the WMM was beginning to exceed the official military specification for accuracy (one degree in declination). BGS and NOAA investigated the field changes responsible for this inaccuracy and subsequently released an updated model in September 2018 that will fully meet the specification from 2015.0 through to 2020.0.

Our analysis showed that the forecast of the 2015 WMM diverged from observed variations in the core magnetic field due to enhanced field (secular) acceleration, which is particularly difficult to predict. Because of this known unpredictability, models such as the WMM generally simplify forecasts of field change by discounting acceleration. Normally this is acceptable, for example when representing average field behaviour over



Difference between rate of change of field intensity (F) given by the original WMM2015 and the updated WMM2015v2 at 2017.5. Stronger colours indicate areas of unpredictable field acceleration

a 5 year period. However, the 2015 release unfortunately coincided with a large and rapid change in acceleration known as a 'geomagnetic jerk' and an accelerated drift in the location of the Northern magnetic (dip) pole. These features could only be detected after the event.

The revised WMM was released in September, though some supporting materials were delayed in the US due to a government shutdown affecting NOAA in December 2018 and January 2019.The revised WMM and the rapid movement of the north magnetic pole led to significant public and media attention for BGS that extended into early 2019.

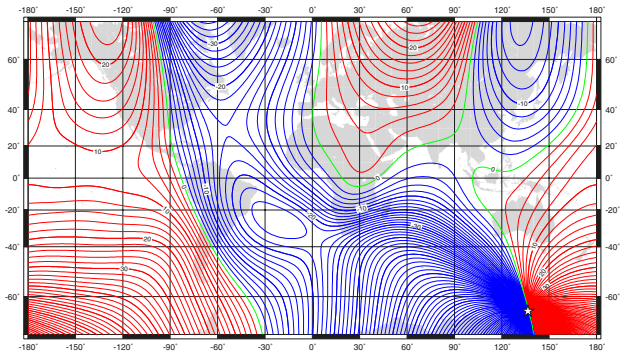
Swarm satellite mission data products

We are further developing our 'fast-track magnetosphere model' product, part of the official ESA Swarm mission product suite, from 2018 through 2020. Currently this Swarm magnetospheric model describes an external dipole field, representing the magnetic field of the dipolar parts of the equatorial ring current, magneto-tail currents and magnetopause currents, and calculated from data on each 90-minute orbit of the Swarm satellite constellation.

This model is being enhanced to include greater spatial and temporal resolution to enable rapid assessment of the strength of the global magnetospheric field, facilitating more timely analysis and the modelling of global trends in the field.

Edinburgh Parallel Computing Centre collaboration

Our collaboration with Dr Nick Brown of the Edinburgh Parallel Computing Centre (EPCC), University of Edinburgh ended in late 2018. This competitively won grant had funded development of the existing BGS field modelling code to add capability in larger scale computations with significantly greater numbers of parameters. This collaboration now allows us to produce models that are far more complex, spatially and temporally, and has taken advantage of advances in parallel computing technology and practice, and the facilities of the Edinburgh ARCHER computing cluster. We will incorporate these improvements into future BGS field models such as the annually revised BGS Global Geomagnetic Model (BGGM).



Declination (magnetic variation) at 2015.0 from the World Magnetic Model (WMM2015v2). Red - positive (east), blue - negative (west), green - zero (agonic line). Contour interval is 2°, white star is location of a magnetic pole and projection is Mercator. This is an example of an isogonic chart. Credit: British Geological Survey (UK Research and Innovation)

Ross Priory on Loch Lomond, owned by the University of Strathclyde, hosted a conference on Optically-Pumped Magnetometry in September 2018

Student and visitor activities

The Geomagnetism team welcomes academic and other visitors from around the world. We also have a number of PhD and MSc students collaborating with our staff, who use BGS data and infrastructure to complete their own research projects.

Visitors

Sean Blake (Trinity College Dublin) spent a week at BGS in January 2018 finalising a collaborative paper on Geomagnetically Induced Currents (GIC) in the Irish high voltage transmission network, before taking up a research position at NASA Goddard Space Flight Center.

As part of an international project collaboration with University of Otago, funded by the New Zealand government, Tim Divett spent two weeks in Edinburgh in May. Ellen Clarke and Alan Thomson of BGS visited Dunedin for two weeks in October to collaborate with Tim Divett and Craig Rogers on GIC research and participate in the close-of-project workshop. Gemma Richardson also visited Dunedin in July for collaborative research.

BGS hosted the Quantum Magnetometry Group from University of Strathclyde in September. The Strathclyde team demonstrated their optically pumped caesium magnetometer and Dr Stuart Ingleby and Paul Griffin of the University discussed their work on implementing a technique called Double-Resonance to create a vector field instrument. Ciaran Beggan subsequently attended a workshop in Glasgow on industrial applications of optically pumped magnetometers.

Dr Grace Cox (University of Liverpool) visited Edinburgh in July to work on a scientific paper with Will Brown on standardising Python code to access and analyse magnetic secular variation data.

In November, BGS hosted three scientists from the BMKG institute in Indonesia including Dr Suhadi. Chris Turbitt helped our visitors test four newly purchased magnetometers at Eskdalemuir. They also spent a day in Edinburgh speaking to the Geomagnetism Team.

Students

BGS currently co-supervise three PhD students funded under the NERC DTP programmes at Edinburgh and Leeds Universities. The BGS BUFI programme also part-funds these scholarships. We

Grace Cox and Will Brown working at the Lyell Centre, Edinburgh (July 2018)

also co-supervise MPhil and MSc projects at the University of Edinburgh.

Ashley Smith is in his final year of a PhD at Edinburgh investigating the potential for improvements in modelling of crustal magnetic fields in the polar regions using Swarm satellite data. The strength and variability in auroral ionospheric currents make the recovery of the static crustal field particularly difficult in this part of the world.

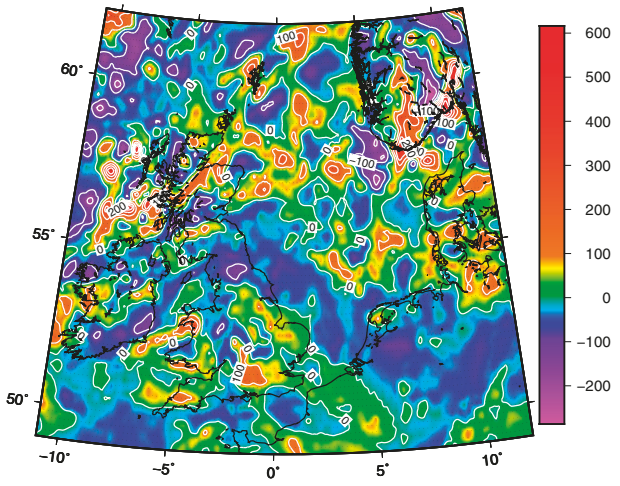
Maurits Metman (University of Leeds) is also in his final year of research into the large-scale changes of the magnetic field in the core that can be ascribed to diffusion of the magnetic field. Maurits visited for two months between April and June and worked on combining core flow modelling with diffusion to improve predictions of magnetic field change over short time periods of one to ten years.

Hannah Rogers completed the first year of her Edinburgh University PhD, investigating the use of Slepian functions in modelling the magnetic field from satellite vector data.

Relly Margiono, an MPhil student at the University of Edinburgh, continued his research using data from Indonesian observatories to examine the occurrence of magnetic jerks in that region of the world. He used the code developed by Will Brown and Grace Cox to analyse his data.

Jacob Langley, a 6th year school student, spent three days with the Geomagnetism team in July as part of his work experience.

Ellen Clarke, Tim Divett, Gemma Richardson, Alan Thomson and Ciaran Beggan (May 2018)



Vertical (Z) component of a spherical harmonic degree 1440 crustal field model over the North Sea

Advances in geomagnetic referencing for the oil industry

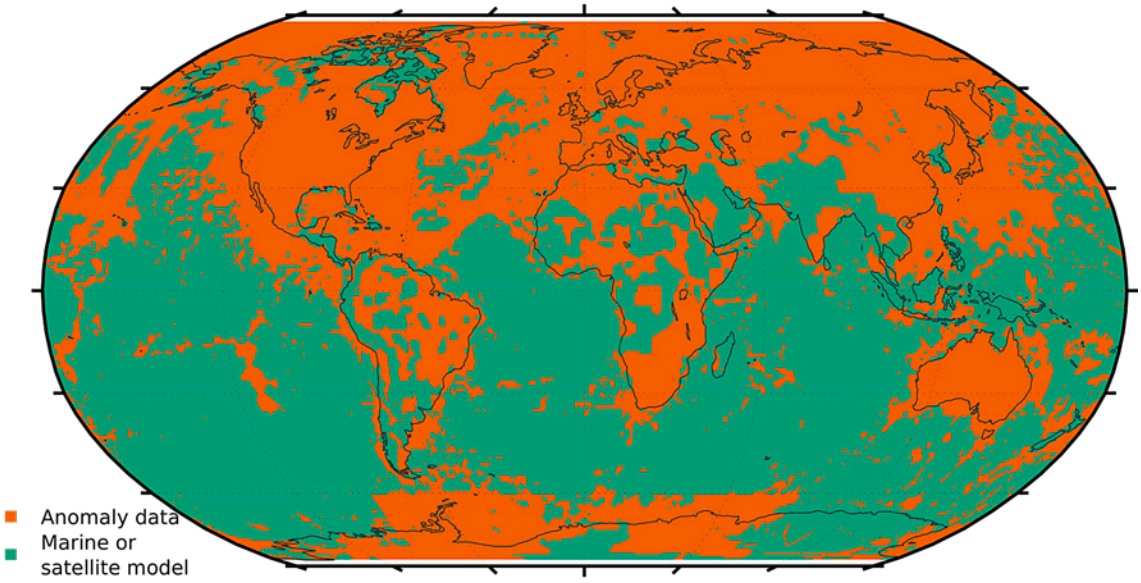
The Geomagnetism Team provides geomagnetic referencing services to the oil industry. Our BGS Global Geomagnetic Model (BGGM), In-Field Referencing (IFR, also known as IFR1 or CA) and Interpolation In-Field Referencing (IIFR or IFR2) services help to increase the accuracy of wellbore positioning across fields worldwide. Significant advances were made in 2018, to better characterise the uncertainties that we provide along with our geomagnetic data.

The BGGM2018 was released in April 2018 and, as first introduced in BGGM2017, included provision of scalable one-sigma magnetic field error estimates. These uncertainties are equivalent to one standard deviation for the magnetic field value at a given time and position, and can be combined with estimates of other sources of uncertainties in the position and heading of the drill-string by the user.

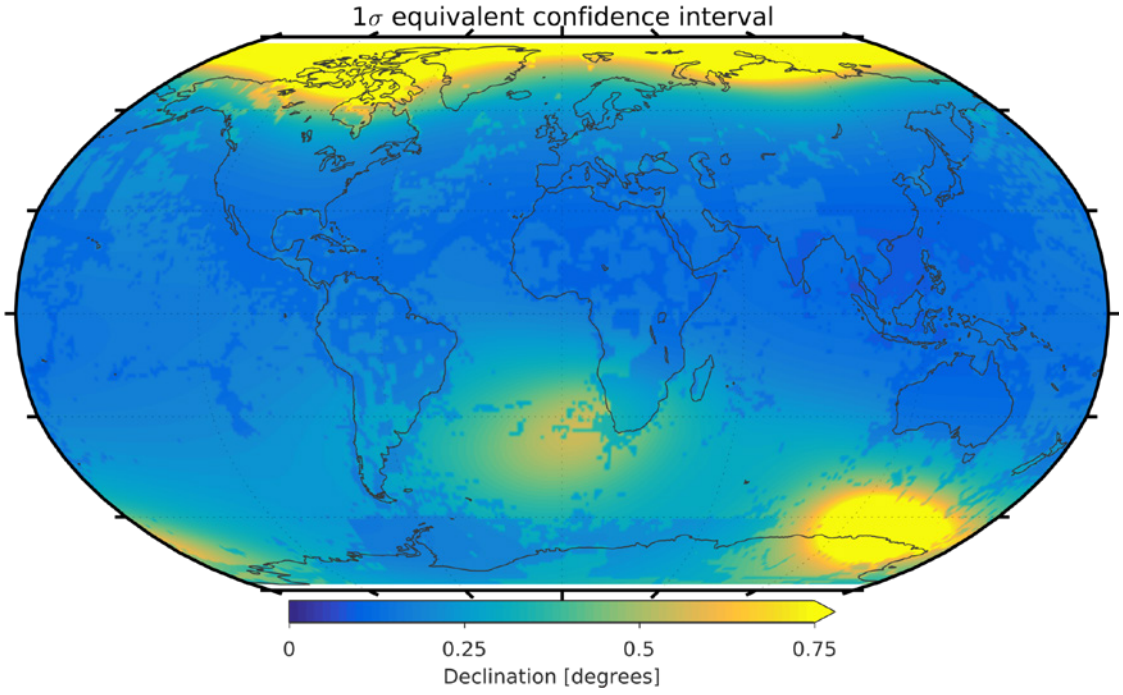
During 2018, the Geomagnetism Team has continued the development of these uncertainty estimates, expanding our existing published approach with a thorough analysis of uncertainties from the wide range of magnetic sources in our field models. This, coupled with our development of high-resolution crustal field models (e.g. spherical harmonic degree 800 (~50 km) to 1440 (~28 km)), leads to an advance towards more complete and robust provision of directional information for our geomagnetic referencing service customers. It should be noted that the increased resolution offered by such high-resolution crustal models does not replace the utility of IFR, where the highest resolution local measurements of crustal fields are leveraged fully, in a manner not possible on a global scale with uneven data coverage.

The error model in development aims to combine several factors and sources of uncertainty. The high-resolution crustal field model is compared to independent ground survey measurements to gauge remaining omitted signal, and combined with information quantifying the spatial

resolution of crustal field measurement. This is necessary as while some areas are covered by dense air- and ship-borne surveys, other regions are only covered by satellite measurements of significantly lower resolution. Further to this, reduced uncertainties in well-known and well-surveyed hydrocarbon fields are factored in. We also consider the accuracy of our forecasting of the future field of Earth's core, and typical magnitudes of variations of external disturbance fields at ground observatories, and their spatial pattern. Together, this results in a complex global map of uncertainties associated with magnetic model estimates, which should help more accurately assess wellbore position.



Scaling for uncertainties, derived from the density and type of data as given by the World Digital Magnetic Anomaly Map (version 2) and by accurate surveying of hydrocarbon areas. Orange areas are dominated by high-resolution crustal anomaly data, green areas are dominated by lower resolution satellite or marine model information



Improved total uncertainty estimate map of modelled declination

Survey equipment set-up for Loch Ness absolute vector measurements

Validating the In-Field Referencing (IFR) method around Loch Ness

As part of a research study with a commercial partner, BGS made a number of absolute vector measurements of the magnetic field around Loch Ness. We compared these measurements to modelled values from an IFR field model set up specifically for the area. We find that the IFR values match the measurements within the usual quoted uncertainties for Declination, Inclination and Total Field. This outcome reinforces our confidence in BGS IFR services to the oil industry.

In-Field Referencing (IFR) is a technique used by BGS to estimate the contribution to the magnetic field vector from both the global main field and the local crustal field. The methodology combines the output from the BGGM with the magnetic field vector computed from a mathematical transformation of regional aeromagnetic data. IFR has been used successfully for decades to provide magnetic reference data for directional drilling.

In early 2018, a commercial partner placed a plastic pipe into Loch Ness, taking advantage of its steeply sloping sides to mimic a sub-surface borehole. The pipe's position was accurately surveyed to give an estimate of its location in three dimensions to within a few metres. The pipeline was around 600 m long and was placed on the southern side of the loch, approximately 20 km south of Inverness.

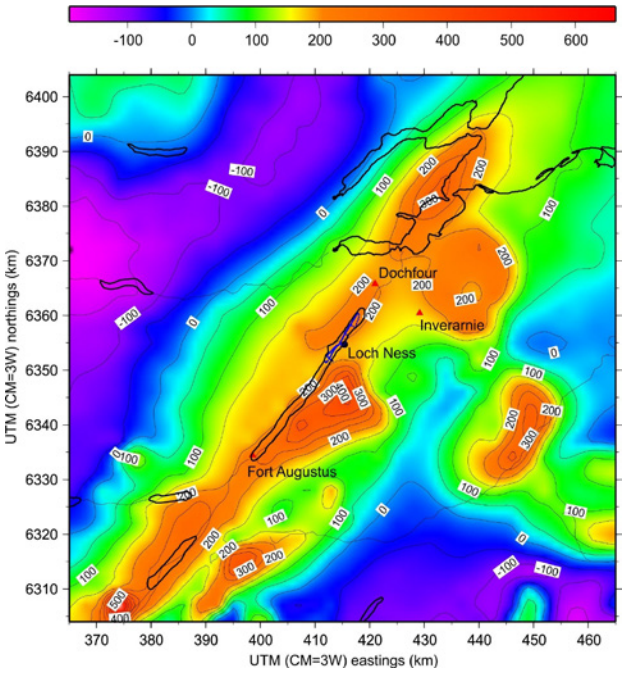
In a joint research project, we investigated how accurate geomagnetic field estimates and the associated uncertainties were for the Loch Ness area. Three sets of data were available to compute and validate IFR in the area around Loch Ness. The first was the BGS total field aeromagnetic dataset for the UK. The second set consisted of total field measurements collected by our partner using a boat-towed magnetometer on Loch Ness. Around 11 400 measurements were made over four hours along a 12 km long section of the loch. Finally, several manual vector ground observations were made by BGS in late April and early-May at three separate sites: Fort Augustus, Dochfour and Inverarnie, all located within 20 km of the pipe.

The aeromagnetic data were the primary source for the IFR transformation that

Site	Difference with respect to BGGM2018			Difference with respect to IFR		
	Dec(°)	Inc(°)	F (nT)	Dec(°)	Inc(°)	F (nT)
Fort Augustus (FOR)	0.247	0.076	139.3	0.145	0.005	-112.4
Inverarnie (INV)	-0.027	-0.076	147.4	0.026	-0.036	-24.1
Dochfour (DOC)	0.001	0.079	194.3	-0.004	-0.018	-15.4
Mean	0.074	0.026	160.3	0.056	-0.016	-50.6
Mean (without FOR)	-0.013	0.002	170.9	0.011	-0.027	-19.8

Difference of vector observations compared with BGGM2018 and the more accurate IFR model values

gives the vector field. The total field measurements collected from the boat were used to set the absolute level of the IFR setup prior to computation. Vector measurements of declination and inclination at the three sites were used to confirm the IFR output and to check that the modelled value matched the observed, within the expected uncertainty. For declination, inclination and total field this industry-defined desired uncertainty is 0.1°, 0.05° and 50 nT (at one standard deviation), respectively.



Contour plot of the BGS aeromagnetic anomaly data (units: nT). Location of the Loch Ness pipe (black dot), the absolute field measurements made on the loch (blue dots) and the sites of the three vector observation sites (red triangles) are also shown

A comparison of the measured vector data with the modelled data is given in the Table. This shows that measurements from Dochfour and Inverarnie are well within the expected uncertainty of the IFR technique. However, data from Fort Augustus is outside the desired uncertainty. Further investigation showed that the Dochfour and Inverarnie sites are underlain by sandstones but the Fort Augustus survey site sits on granitic rock, which is highly magnetically anomalous. The latter breaks a basic assumption of the IFR technique that any magnetic sources should be suitably distant from the measurement surface. Here the granites are close to the surface.

If we ignore the Fort Augustus data, since it is not representative of a hydrocarbon basin, we can see that the mean absolute differences are 0.01° in Declination, 0.02° in Inclination and around 20 nT in Total Field (F). Although there are only two vector measurements, this is still a useful confirmation that IFR models (which also contain the BGGM) correctly capture global and crustal magnetic field values. It also confirms that IFR models out-perform the BGGM–only model.

Gemma Richardson being videoed doing the live space weather forecast during European Space Weather Week

Space weather and geomagnetic hazard

During 2018, the Geomagnetism Team continued to provide and develop space weather applications and services. Developments have included an upgrade of our real-time space weather monitoring services and creation of a new magnetic activity index, as a proxy for Geomagnetically Induced Current in the UK power transmission network. We have also continued our space weather research activities under the SWIGS project and presented our work at national and international conferences.

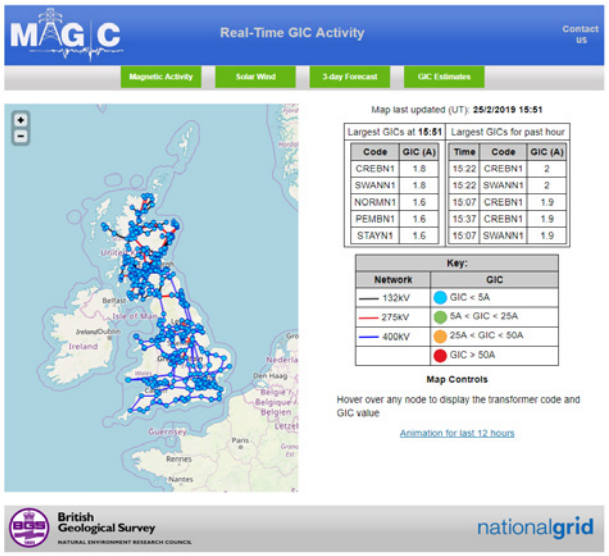
MAGIC

At BGS we operate a real-time service called 'Monitoring and Analysis of GIC' (MAGIC) for National Grid. As part of this service, we model the electric field on the surface of the Earth and model Geomagnetically Induced Currents (GIC) that flow in the UK power transmission network, both caused by space weather. During 2018, we updated our modelling process to provide surface electric fields that are more realistic. We also incorporated a more up-to-date version of the power network, based on the 2017 Electricity Ten Year Statements from National Grid, to improve our estimate of where hazardous GIC may strike.

A new index of GIC activity

The widely known and widely used Kp magnetic activity index helps identify magnetic storms that may pose a hazard to power system operations. However, the Kp index is not truly suited to this purpose, as GIC vary locally much faster than Kp, which is derived from global magnetic activity sampled over a three hour interval. In addition, the quasi-logarithmic nature of the Kp index implies that its maximum possible value (9o) covers a wide range of storms and impacts, some of which might actually not be particularly damaging to network transformers and safety equipment.

We have therefore developed a new index, which we currently call B_{GIC}. B_{GIC} is derived from magnetic field data measured at the Eskdalemuir observatory and it more accurately indicates the potential GIC risk to the UK power grid. The new index is now running operationally on BGS servers and produces updated values every 5 minutes. The index closely matches the Kp scale at low activity levels, but also extends the scale beyond the Kp maximum, to cover severe magnetic



The MAGIC real-time GIC monitoring system showing an updated network model

storms that might be expected only once in one or two hundred years.

Royal Astronomical Society 'Specialist Discussion' meeting

In March 2018, Ciaran Beggan co-convened, with colleagues from University of Lancaster and Met Office, a Specialist Discussion Meeting at the Royal Astronomical Society on 'The ground effects of space weather'. He also wrote a review of the meeting for the RAS Astronomy & Geophysics journal. The meeting comprised a range of talks from both academia and industry, on topics such as policy and the evaluation of system vulnerability. The meeting also discussed space weather impacts on airlines, rail and power grids, and took a closer look at the impact of the March 1989 severe storm on the Quebec power system. Gemma Richardson presented the new B_{GIC} GIC activity index at the meeting.

European Space Weather Week

The 15th European Space Weather Week was held in Leuven, Belgium, from 5th to 9th November 2018. BGS presented one talk, two posters and a 'live space weather forecast' (Gemma Richardson). Ellen Clarke featured in an ESA video 'Ask a space weather researcher (part 2),' as part of a series of ESA videos and social media outputs produced to celebrate space weather research.

Following research within the SWIGS project, Gemma Richardson presented 'Initial results from pipeline modelling in the UK' during the session on 'Geomagnetic storms—Ground and near-Earth space weather impacts'. Gemma described first results from the Team's brand new capability in modelling pipe-to-soil (PSP) potentials in the UK gas transmission network. Significant PSP can lead to increased pipe steel corrosion and shortened pipe lifetime.

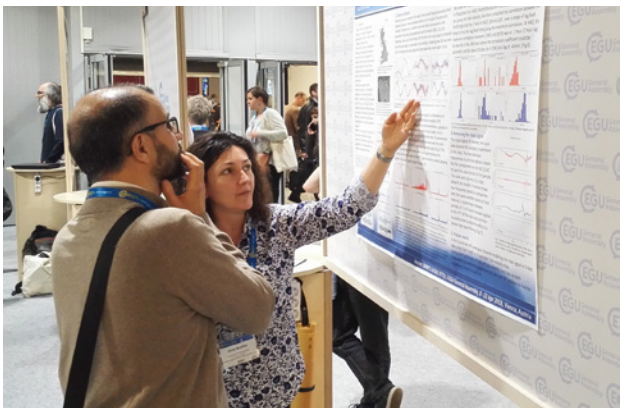
Juliane Huebert also showed some early SWIGS research when she presented a poster describing 'differential magnetometer measurements of GIC in the UK power grid', highlighting our hardware development and some early measurement results. Ellen Clarke presented a poster on behalf of John Williamson describing work on the 'Evaluation and comparison of geomagnetic activity forecasts'.

New Zealand Ministry of Business, Innovation and Education project

In July 2018, Gemma Richardson returned to New Zealand as part of the MBIE collaboration with the University of Otago, on Mitigating Emerging Risks to New Zealand's Electrical Network. During her two-week visit, she developed the BGS GIC modelling code to provide more detailed outputs, including individual line and transformer currents. She also investigated the use of 'shapefile' information to provide more realistic transmission line paths that, in time, will replace the straight-line segment method that we currently employ.

Ellen Clarke and Alan Thomson also travelled to New Zealand, in October, for the final meeting of the MBIE project. At this meeting, final research results were presented by our New Zealand collaborators. Ellen and Alan presented on parallel research activities at BGS and discussed options for further collaboration.

Outreach



Orsi Baillie presenting her poster at the EGU Assembly in Vienna

Publications and knowledge exchange

A wide variety of outputs are produced by the Geomagnetism Team, including papers in scientific journals, commissioned reports, posters, talks and presentations.

Scientific journal publications

Published 2018

Abbassi, B, Cheng, L Z, Richards, J P, **Hübert**, **J**, Legault, J M, Rebagliati, M, Witherly, K. (2018) Geophysical properties of an epithermal Au-Ag deposit in British Columbia, Canada, *Interpretation* 2018 6:4, T907-T918, https://doi.org/10.1190/INT-2017-0232.1

Beggan, **C D**, **Billingham**, **L**, **Clarke**, **E**. (2018) Estimating external magnetic field differences at high geomagnetic latitudes from a single station. *Geophysical Prospecting*. https://doi.org/10.1111/1365-2478.12641

Beggan, **C D**, Marple, Steve R. (2018) Building a Raspberry Pi school magnetometer network in the UK. *Geoscience Communications*, 1. 25-34. https://doi.org/10.5194/gc-1-25-2018

Beggan, **C D**, Musur, M. (2018) Observation of Ionospheric Alfven Resonances at 1-30 Hz and their superposition with the Schumann Resonances. *Journal of Geophysical Research Space Physics*. https://doi.org/10.1029/2018JA025264

Beggan, **C D**, Whaler, K.A. (2018) Ensemble Kalman filter analysis of magnetic field models during the CHAMP-Swarm gap. *Physics of the Earth and Planetary Interiors*, 281. 103-110. https://doi.org/10.1016/j.pepi.2018.06.002

Beggan, **C D**, Wild, J, Gibbs, M. (2018) The ground effects of severe space weather. Astronomy and Geophysics, 59 (4). 4.36-4.39. https://doi.org/10.1093/astrogeo/aty194

Blake, S P, Gallagher, P T, Campanyà, J, Hogg, C, **Beggan**, **C D**, **Thomson**, **A W P**, **Richardson**, **G S**, Bell, D. (2018) A detailed model of the Irish High Voltage Power Network for simulating GICs. *Space Weather*, 16 (11). 1770-1783. https://doi.org/10.1029/2018SW001926

Campanyà, J, Gallagher, P T, Blake, S P, Gibbs, M, Jackson, D, **Beggan**, **C D**, **Richardson**, **G S**, Hogg, C. (2018) Modeling geoelectric fields in Ireland and

the UK for space weather applications. *Space Weather*, 16. https://doi.org/10.1029/2018SW001999

Cox, G A, **Brown**, **W J**, **Billingham**, **L**, Holme, R. (2018) MagPySV: a Python package for processing and denoising geomagnetic observatory data. *Geochemistry, Geophysics, Geosystems*. https://doi.org/10.1029/2018GC007714

Divett, T, **Richardson**, **G S**, **Beggan**, **C D**, Rodger, C J, Boteler, D H, Ingham, M, Mac Manus, D H, **Thomson**, **A W P**, Dalzell, M. (2018) Transformer-level modeling of geomagnetically induced currents in New Zealand's South Island. *Space Weather*, 16 (6). 718-735. https://doi.org/10.1029/2018SW001814

Hübert, **J**, Whaler, K, Fisseha, S. (2018) The electrical structure of the Central Main Ethiopian Rift as imaged by magnetotellurics: Implications for magma storage and pathways. *Journal of Geophysical Research: Solid Earth*, 123, 6019– 032. https://doi.org/10.1029/2017JB015160

Lee, B M, Unsworth, M J, **Hübert**, **J**, Richards, J P, Legault, J M. (2018), 3D joint inversion of magnetotelluric and airborne tipper data: a case study from the Morrison porphyry Cu–Au–Mo deposit, British Columbia, Canada. *Geophysical Prospecting*, 66: 397-421. doi:10.1111/1365-2478.12554

Lockwood, M, Chambodut, A, Barnard, L A, Owens, M J, **Clarke**, **E**, Mendel, V. (2018) A homogeneous aa index, 1. Secular variation. *Journal of Space Weather and Space Climate*, 8, A53. https://doi.org/10.1051/swsc/2018038

Lockwood, M, Finch, I D, Chambodut, A, Barnard, L A, Owens, M J, **Clarke**, **E**. (2018) A homogeneous aa index, 2. Hemispheric asymmetries and the equinoctial variation. *Journal of Space Weather and Space Climate*, 8, A58. https://doi.org/10.1051/swsc/2018044

Oughton, E J, Hapgood, M, **Richardson**, **G S**, **Beggan**, **C D**, **Thomson, A W P**, Gibbs, Mark; Burnett, Catherine; Gaunt, C, Trevor; Trichas, Markos; Dada, Rabia; Horne, Richard B. (2018) A risk assessment framework for the socio-economic impacts of electricity transmission infrastructure failure due to space weather: an application to the United Kingdom. *Risk Analysis*. https://doi.org/10.1111/risa.13229

Published and to appear 2019 (at March 2019)

Macmillan, S, and **Taylor**, **T**. (2019). A magnetic prediction comes true. Astronomy & Geophysics, 60(1), https://doi.org/10.1093/astrogeo/atz041, Feb 2019.

Margiono, R, **Turbitt**, **C W**, **Beggan**, **C D**, Whaler, K A. (2019) Improvements of geomagnetic data quality at Indonesian observatories. Conrad Observatory Journal 5 - Special Issue IAGA Workshop 2018, p.31

Martyn, **T P**, **Swan**, **A P**, **Taylor**, **T L**, **Turbitt**, **C W**. (2019) Differential Magnetometer System in Support of Space Weather Impact Modelling. Conrad Observatory Journal 5 - Special Issue IAGA Workshop 2018, p.18

Rogers, H F, **Beggan**, **C D**, Whaler, K A. (2019) Investigation of regional variation in core flow models using spherical Slepian functions. Earth, Planets and Space, 71:19 https://doi.org/10.1186/s40623-019-0997-7

Other publications

1 BGS Open Report: **Thomson**, **Alan W P**, ed. Geomagnetism review 2017. British Geological Survey, 40pp. (OR/18/036) www.geomag.bgs.ac.uk/documents/reviews/Geomagnetism_Review_2017.pdf

20 Customer Reports (UK survey & OS; oil industry services)

Report for CERN on the natural sources of geomagnetic field variations (**C Beggan**). :

Natural Geomagnetic fields: Review for CERN Linear Collider, Balazs Heilig, Ciaran Beggan and János Lichtenberger,

Report, June 2018, http://cds.cern.ch/record/2643499

108 Observatory Monthly Bulletins: http://www.geomag.bgs.ac.uk/data_service/data/bulletins/bulletins.html

Bi-monthly column on Space Weather for Royal Institute of Navigation's 'Navigation News'

Technical note concerning Out-of-Cycle Update of the US/UK World Magnetic Model for 2015-2020: BGS and NOAA. doi: 10.25921/xhr3-0t19

Conference presentations, posters and related activities

RAS specialist Discussion meeting 'Ground Effects of Severe Space Weather', London, March
1 presentation (Richardson)
1 co-organiser (Beggan)

EGU General Assembly 2018, Vienna, Austria, April
1 talk (Beggan)
5 posters (Baillie, Beggan, Brown)

Geomagnetism Advisory Group annual meeting, Edinburgh, May
5 presentations (Thomson, Turbitt, Macmillan, Hamilton, Clarke, Flower, Richardson)

IAGA Observatories Workshop, Hernstein, Austria, June
1 public lecture (Thomson)
1 presentation (Martyn)
1 observatory scientists training course
2 posters (Taylor and Martyn)

24th Electromagnetic Induction Workshop, Helsingør, Denmark, August
1 poster (Huebert)

MIST public Engagement Workshop, Leicester, September
1 presentation (Beggan and Richardson)

75 Years Of Geomagnetic Measurements Of The Romanian Centenary, Bucharest, Romania, October
2 presentations (Turbitt, Flower – "INTERMAGNET at 30: Past developments and future plans")

ESA Swarm 8th Data Quality Workshop, Frascati, Italy, October
2 presentations (Brown)

European Space Weather Week 15, Leuven, Belgium, November
1 presentation (Richardson)
2 posters (Huebert and Williamson)
'Live Forecast' (Richardson)

AGU Fall Meeting 2018, Washington, USA, December
1 presentation (Thomson)

Geomagnetism Team seminars, Edinburgh
17 presentations throughout the year by team members, students and visitors

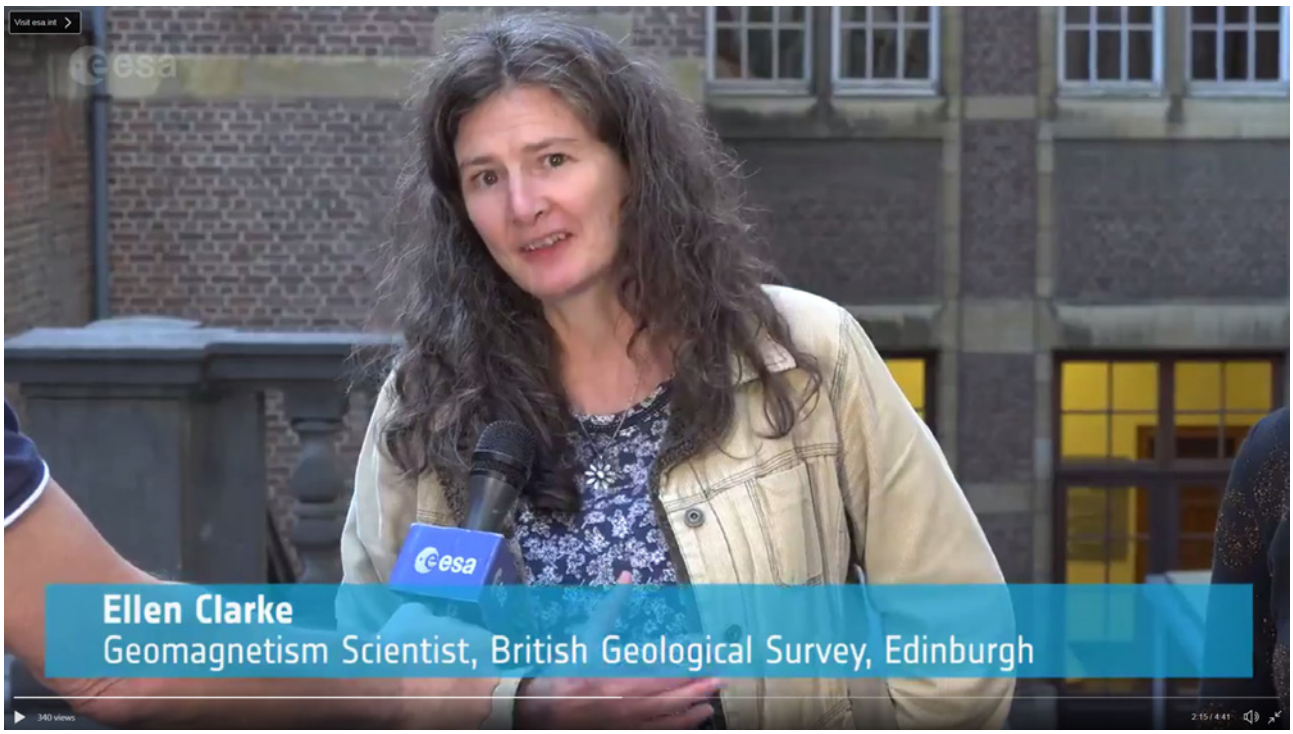
Some other notable outputs

Observatory tours

- Tour of Eskdalemuir for the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) in November

Public Lectures, presentations and demonstrations

- Edinburgh Science Festival, April
- Lyell Centre Doors Open day, demonstrations and talk, September (Richardson, Flower, Huebert, Wang)
- Midlothian Science Festival 'Let's Explore Earth!', October (Brown and Richardson)
- Chris Turbitt with Peter Harvey (Met Office) Tweeddale Society lecture on Eskdalemuir Observatory, November
- Ashley Smith, Beggan and Brown presentations at 'Astronomy on Tap', Edinburgh, November and December



Video credit: European Space Agency CC-BY-SA 3.0

Media

Ellen Clarke was interviewed by ESA during European Space Weather Week in November.

Education

University of Edinburgh lectures: Geomagnetism, 8 lectures, Brown and Beggan

Other

- Chris Turbitt demonstrated absolute observations, instruments and observatory operations to delegates at the ISCWSA meeting in Inverness in April.
- Gemma Richardson gave a presentation on GIC modelling to the University of Otago's modellers group in July 2018.
- Visit by Scottish Government Resilience Division (Risk and Assurance) in July. Discussions and presentations on geomagnetic risk to electrical transmission system in Scotland.
- Juliane Hübert gave a presentation at Uppsala University's geophysics seminar series about SWIGS in August 2018.
- Will Brown gave a presentation on Geomagnetic modelling at the MACS collaboration workshop at Heriot-Watt in October 2018.
- Juliane Hübert presented SWIGS work at a joint seminar from Astrophysics & Geophysics at DIAS (Dublin Institute of Advanced Studies) in October 2018.
- Ellen Clarke gave a presentation about magnetic referencing at the University of Otago in October 2018.
- Visit to Scottish Power in November to discuss GIC measurements.
- Juliane Hübert participated in a Native Scientist event for bilingual schoolchildren at Napier University in November 2018.

Ciarán Beggan explains his Raspberry Pi magnetometer at an Astronomy on Tap event (photo courtesy of Astronomy on Tap, Edinburgh)

Outreach activities

The BGS Geomagnetism Team endeavours to share our knowledge with as wide an audience as possible. This means not only delivering high-level research and technical expertise in professional journals and meetings, but also engaging with, and encouraging scientific interest in, people at all levels of knowledge. Here we give some of the highlights of these outreach activities in 2018.

University teaching

From the start of the January semester, Ciarán Beggan and William Brown continued BGS involvement in the delivery of the honours year course on Geomagnetism at the University of Edinburgh. The course is offered to students with geophysics, physics and mathematics backgrounds. Over sixteen lectures and four tutorials, students were taught about the physics of the geomagnetic field and the Earth's core, as well as that of solar magnetic activity and the interaction between the Earth and the solar wind. This teaching benefits from the long-standing BGS expertise in observation, modelling and applied work in geomagnetism.

Edinburgh Science festival

In April, the Team took part in the Edinburgh Science Festival at an event in the Oriam Sports Centre at Heriot Watt University, Edinburgh, where more than 5000 members of the public attended to see the great science on offer from BGS and Heriot Watt. This gave the Geomagnetism Team an excellent opportunity to engage people with the wonders of magnets and the Earth's magnetic field.

Lyell Centre Open day

On 29th September, the Lyell Centre (BGS's home in Scotland) opened its doors to the public to highlight the science we do here. Around 500 visitors came to get involved with hands on exhibits and to listen to public lectures on research from across the Lyell Centre—which houses both BGS and Heriot Watt University staff. The Geomagnetism Team were once again present with magnets, videos of the northern lights, a Raspberry Pi magnetometer showing real-time measurements of the magnetic field, a 'magic planet' showing the changing magnetic field and our very popular

'reversals carpet'. Gemma Richardson also gave a talk on 'The weather in space…. Sunspots, flares, eruptions and the northern lights' which was followed by some very interesting questions.

Midlothian Science festival

The Geomagnetism Team also took part in the Midlothian Science festival at the 'Let's explore Earth' event in October. This event was located in an IKEA store, which gave the opportunity to grab the attention of some people who would perhaps not normally seek out a science event.

Astronomy on Tap

Ciarán Beggan, William Brown and PhD student Ashley Smith continued our efforts to engage with new audiences, taking part in evenings organised by the Edinburgh chapter of 'Astronomy on Tap' in November and December. The group brings scientists and their work into pubs across the world with talks aimed at a general audience. Talks on Geomagnetism, BGS's Raspberry Pi magnetometers and geomagnetic field reversals proved popular, and generated very engaging Q&A sessions with the audiences of 60 attendees — perhaps benefiting from the loosening of any inhibitions over asking questions in public!

Guanren Wang demonstrating magnets at the Edinburgh International Science Festival

Selected glossary, acronyms and links

AGU	*American Geophysical Union (sites.agu.org/)*
ARCHER	*UK National Supercomputing Service (http://www.archer.ac.uk/)*
BGGM	*BGS Global Geomagnetic Model (www.geomag.bgs.ac.uk/bggm.html)*
BGS	*British Geological Survey (www.bgs.ac.uk)*
BMKG	*Badan Meteorologi, Klimatologi, dan Geofisika/Meteorology, Climatology, and Geophysical Agency (https://www.bmkg.go.id/)*
BUFI	*BGS University Funding Initiative (http://www.bgs.ac.uk/research/bufi/)*
CA	*Crustal Anomaly*
CERN	*European Organization for Nuclear Research (https://home.cern/)*
CHAMP	*German magnetic survey satellite (www-app2.gfz-potsdam.de/pb1/op/champ)*
DISC	*Data, Innovation and Science Cluster supporting the ESA Swarm mission*
DMM	*Differential Magnetometer Method for detecting GIC in power lines*
DOI	*Digital Object Identifier*
DTP	*Doctoral Training Partnership*
eCSE	*Embedded Computational Science and Engineering (eCSE) programme.*
EGU	*European Geosciences Union (www.egu.eu)*
EHO	*The Earth Hazards and Observatories science directorate of BGS (http://www.bgs.ac.uk/research/earthHazards/home.html)*
EPCC	*Edinburgh Parallel Computing Centre*
EPOS	*European Plate Observing System (www.epos-ip.org/)*
ERIC	*EPOS 'European Research Infrastructure Consortium'*
ESA	*European Space Agency (www.esa.int)*
EU	*European Union*
ESWW	*European Space Weather Week. (sidc.oma.be/esww13)*
FMC	*Fort McMurray magnetic observatory (Canada)*
G-ESA	*Geomagnetic Conditions Expert Service Centre (http://swe.ssa.esa.int/geomagnetic-conditions) Space Weather Operations Centre*
GFZ	*GeoForschungsZentrum/German Research Centre for Geosciences(https://www.gfz-potsdam.de/en/home/)*
GIC	*Geomagnetically Induced Currents (a natural hazard to power systems)*
Git	*An open source distributed version control system (https://git-scm.com/)*
GitLab	*Git-repository managment tool (https://about.gitlab.com/)*
GLONASS	*Globalnaya Navigazionnaya Sputnikovaya Sistema (Russian GNSS) (https://www.glonass-iac.ru/en/)*
GPS	*Global Positioning System*
HPC	*High Performance Computing*
Horizon 2020	*An EU Research and Innovation programme (https://ec.europa.eu/programmes/horizon2020/)*
IAGA	*International Association of Geomagnetism and Aeronomy (www.iugg.org/IAGA)*
ICSU	*International Science Council (www.icsu-geounions.org)*
IGRF	*International Geomagnetic Reference Field (www.ngdc.noaa.gov/IAGA/vmod/igrf.html)*
IIFR/IFR	*Interpolation In-Field Referencing/In-Field Referencing. (www.geomag.bgs.ac.uk/data_service/directionaldrilling/ifr.html)*
INTERMAGNET	*International Magnetometer Network: a global network of magnetic observatories operating to common standards.(www.intermagnet.org)*

INDIGO	*Collaborative effort of BGS and Royal Observatory Belgium, supplying developing nations with magnetometers (described in pubs.usgs.gov/of/2009/1226)*
ISCWSA	*Industry Steering Committee on Wellbore Survey Accuracy. (iscwsa.net)*
ISGI	*International Service for Geomagnetic Indices (www.isgi.unistra.fr)*
IUGG	*International Union of Geodesy and Geophysics (www.iugg.org)*
IT	***I**nformation Technology*
JCO	*Jim Carrigan (magnetic) Observatory (Alaska)*
Kp	*A measure of mid-latitude planetary average geomagnetic activity, on a scale of 0-9.*
LEMI	*Laboratory of Electromagnetic Innovations (www.lemisensors.com/)*
Linux	*A family of open source Unix-like operating systems*
MAGIC	*Monitoring and Analysis of GIC. A GIC analysis service for the National Grid*
MBIE	*New Zealand Ministry of Business, Innovation and Education*
MEME	*Model of the Earth's Magnetic Environment (http://geomag.bgs.ac.uk/research/modelling/MEME.html)*
Met Office	*UK Meteorological Office (www.metoffice.gov.uk)*
MIST	*Magnetosphere, Ionosphere and Solar-Terrestrial UK scientific community (www.mist.ac.uk/)*
MOSWOC	*Met Office Space Weather Operations Centre*
MT	*Magneto-telluric*
NASA	*National Aeronautics and Space Administration (https://www.nasa.gov/)*
NATO	*North Atlantic Treaty Organization (https://www.nato.int/)*
NCEI	*NOAA's National Centers for Environmental Information (https://www.ncei.noaa.gov/)*
NERC	*Natural Environment Research Council (www.nerc.ac.uk)*
NOAA	*National Oceanographic and Atmospheric Administration (USA)*
OS	*Ordnance Survey (www.ordnancesurvey.co.uk)*
PSP	*Pipe-to-soil potential (in gas transmission pipelines)*
QA	*Quality Assurance*
QDD	*INTERMAGNET Quasi-Definitive Data*
QNX	*A commercial Unix-like real-time operating system (www.qnx.com)*
Raspberry Pi	*A small, low-cost computer (https://www.raspberrypi.org)*
RAL	*Rutherford Appleton Laboratory (STFC)*
RAS	*Royal Astronomical Society*
RFI	*Radio Frequency Interference*
RIN	*Royal Institute of Navigation (www.rin.org.uk/general/Navigation-News)*
SBL	*Sable Island magnetic observatory (Canada)*
SPE	*Society of Petroleum Engineers (www.spe.org)*
STFC	*Science and Technology Facilities Council*
Swarm	*ESA three-satellite 'mini-constellation' for magnetic field surveying. (http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm)*
SWENET	*Space Weather Network (ESA)*
SWIGS	*Space Weather Impact on Ground-based Systems (www.geomag.bgs.ac.uk/research/SWIGS)*
SWPC	*Space Weather Prediction Center (USA)*
TCD	*Trinity College Dublin (www.tcd.ie)*
UKRI	*UK Research and Innovation (https://www.ukri.org/)*
WDC	*World Data Centre, part of the ICSU World Data System (www.wdc.bgs.ac.uk)*
WDS	*World Data System (www.icsu-wds.org)*
WMM	*World Magnetic Model (https://geomag.bgs.ac.uk/research/modelling/WorldMagneticModel.html)*

The Geomagnetism Team 2018

Staff changes

David Scott retired from BGS in September. Latterly, David supported major IT and webpage developments for the Team and we thank David for his dedication and hard work on all Geomagnetism projects.

Dr Juliane Huebert joined the team in February as a post-doctoral researcher on the NERC SWIGS project. Juliane will support the development and deployment of field equipment to measure Geomagnetically Induced Currents. She will also work with colleagues at the University of Edinburgh on improved Earth conductivity models for the UK.

Geomagnetism staff 2018

Orsolya (Orsi) Baillie	*Geomagnetism Research, Data Processing and QA*
Brian Bainbridge	*IT and Software Development*
Dr Ciarán Beggan	*Geomagnetism Research*
Claire Brown	*Manager, Eskdalemuir Geomagnetic Observatory*
Dr William Brown	*Geomagnetism Research*
Ellen Clarke	*Geomagnetism Research, Data Processing and QA*
Paul Dickson	*Geomagnetism Business Account Support*
Jane Exton	*IT and Software Development*
Simon Flower	*Technical, IT and Software Development*
Dr Brian Hamilton	*Geomagnetism Research*
Alexander (Sandy) Henderson	*Geomagnetic Data Processing*
Dr Juliane Huebert	*Technical, Geomagnetic Research (from February 2018)*
Thomas Humphries	*Geomagnetic Data Processing and QA*
Dr David Kerridge	*Geomagnetism Research*
Dr Susan Macmillan	*Geomagnetism Research*
Thomas Martyn	*Technical, Observatory Operations, Field Survey*

Sarah Reay	*Geomagnetism Research, Data Processing and QA*
Dr Gemma Richardson	*Geomagnetism Research*
David Scott	*IT and Software Development (retired September 2018)*
Anthony Swan	*Technical, Observatory Operations & Field Survey*
Peter Stevenson	*IT and Software Development*
Timothy Taylor	*Technical, Observatory Operations, Field Survey*
Dr Alan Thomson	*Geomagnetism Research & Geomagnetism Team Leader*
Stephen Tredwin	*Manager, Hartland Geomagnetic Observatory*
Christopher Turbitt	*Technical, Observatory Operations, Field Survey*
Guanren Wang	*Geomagnetic Data Processing and QA*
John Williamson	*Geomagnetic Data Processing and QA*

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